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Logistics Reduction and Repurposing Technology for Long-Duration Space Missions

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One of NASA's Advanced Exploration Systems (AES) projects is the Logistics Reduction and Repurposing (LRR) project, which has the goal of reducing logistics resupply items through direct and indirect means. Various technologies under development in the project will reduce the launch mass of consumables and their packaging, enable reuse and repurposing of items, and make logistics tracking more efficient. Repurposing also reduces the trash burden onboard spacecraft and indirectly reduces launch mass by one manifest item having two purposes rather than two manifest items each having only one purpose. This paper provides the status of each of the LRR technologies in their third year of development under AES. Advanced clothing systems (ACSs) are being developed to enable clothing to be worn longer, directly reducing launch mass. ACS has completed a ground exercise clothing study in preparation for an International Space Station technology demonstration in 2014. Development of launch packaging containers and other items that can be repurposed on-orbit as part of habitation outfitting has resulted in a logistics-to-living (L2L) concept. L2L has fabricated and evaluated several multi-purpose cargo transfer bags for potential reuse on-orbit. Autonomous logistics management is using radio frequency identification (RFID) to track items and thus reduce crew time for logistics functions. An RFID dense reader prototype is under construction and plans for integrated testing are being made. A heat melt compactor (HMC) second generation unit for processing trash into compact and stable tiles is nearing completion. The HMC prototype compaction chamber has been completed and system development testing is under way. Research has been conducted on the conversion of trash-to-gas (TtG) for high levels of volume reduction and for use in propulsion systems. A steam reformation system was selected for further system definition of the TtG technology.

Nomenclature

ACS	=	advanced clothing system
ATV	=	Automated Transfer Vehicle
AES	=	Advanced Exploration Systems
ALM	=	autonomous logistics management
CTB	=	cargo transfer bag
COTS	=	commercial off-the-shelf
CQ	=	crew quarters
DSH	=	Deep Space Habitat
EAM	=	Exploration Augmentation Module
ESM	=	equivalent system mass
EXPRESS	=	EXpedite the Processing of Experiments to Space Station
HI-SEAS	=	Hawaii Space Exploration Analog and Simulation
HMC	=	heat melt compactor
ISS	=	International Space Station

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JPL	=	Jet Propulsion Laboratory
Kg	=	kilogram
LEO	=	low Earth orbit
LRR	=	Logistics Reduction and Repurposing
L2L	=	logistics-to-living
MCTB	=	multi-purpose cargo transfer bag
MMSEV	=	Multi-Mission Space Exploration Vehicle
m^3	=	cubic meter
NASA	=	National Aeronautics and Space Administration
REALM	=	radio frequency identification enabled autonomous logistics management
RF	=	radio frequency
RFID	=	radio frequency identification
SBIR	=	small business innovation research
SE&I	=	Systems Engineering and Integration
3D	=	three-dimensional
TtG	=	trash-to-gas
X-Hab	=	eXploration Habitat

I. Introduction

ALL human space missions, regardless of destination, require significant logistical mass and volume that is directly proportional to mission duration. As exploration missions increase in distance and duration, reduction of logistics becomes even more important since all items may have to be loaded on a single launch vehicle. NASA's Advanced Exploration Systems (AES) Logistics Reduction and Repurposing (LRR) project is completing its third year of technology development. LRR is applying a systematic cradle-to-grave approach to five technologies. The five LRR approaches, depicted in Figure 1, and their corresponding technologies are:

- *Direct reduction of logistical mass*. Use of an advanced clothing system (ACS) to directly reduce the mass and volume of clothing needed. Antimicrobial treatments are applied to current and lighter weight commercial off-the-shelf (COTS) exercise clothing to investigate whether they could be used for longer periods of time. Longer-wear clothing will change the break-even point for laundering (vs. clothing disposal) sufficiently to delay development until Mars surface missions are planned.
- *Improved automated tracking of logistical items in packaging containers and cabins to allow denser logistical packaging at launch and to save on-orbit crew time*. Use of autonomous logistics management (ALM) methods using radio frequency identification (RFID) technologies, three-dimensional (3D) localization, and complex event processing will enable automatic inventory tracking as items move through the crew cabin and between vehicles. ALM will reduce crew time required to locate stored items in densely packed areas and enable the location of lost items.
- *Direct reuse and repurposing of logistical items to avoid flying separate items to meet both functions.* Repurposing of logistics-to-living (L2L) multi-purpose cargo transfer bags (MCTBs) for on-orbit outfitting. MCTBs can be unfolded from a suitcase shaped volume to a flat panel on-oribit so that they can be used for outfitting functions. MCTBs can be used for constructing crew quarters, privacy or sound-adsorbing partitions, contingency water storage or waste water processing units, and soft-sided containers for ALM dense-area RFID readers. For a 1-year mission with four crew members, it is estimated that over half of the approximately 170 cargo transfer bags (CTBs) could be repurposed on-orbit. Reuse of the MCTB logistics carriers prevents the need to fly dedicated items and would save approximately 0.5 m^3 and 140kg.[1]
- *Processing of logistical items to provide a secondary function, increase habitable volume, and enhance life support cycle closure.* Conversion of waste and used logistical items to useable products with a heat melt compactor (HMC). Items are heated and mechanically compacted into stable tiles that can be used for radiation shielding. Additionally, water is recovered for life support processing. For a 1-year mission with four crew members, it is estimated that HMC could recover about 10 m^3 of habitable volume, produce over 900 kg of radiation shielding tiles, and recover 230-720 kg of water.[1]
- *Deconstruction of logistical materials and reconstruction to primary gases or as a means of reducing waste volume through venting.* Reformulation of trash-to-gas (TtG) to make propellant from waste products. Thermochemical processes are used to deconstruct trash to its hydrocarbon constituents and

recombine it to form methane and other gases useful for propellant or life support. For a 1-year mission, it is estimated that TtG could produce up to 1500 kg of methane from waste products.[1]

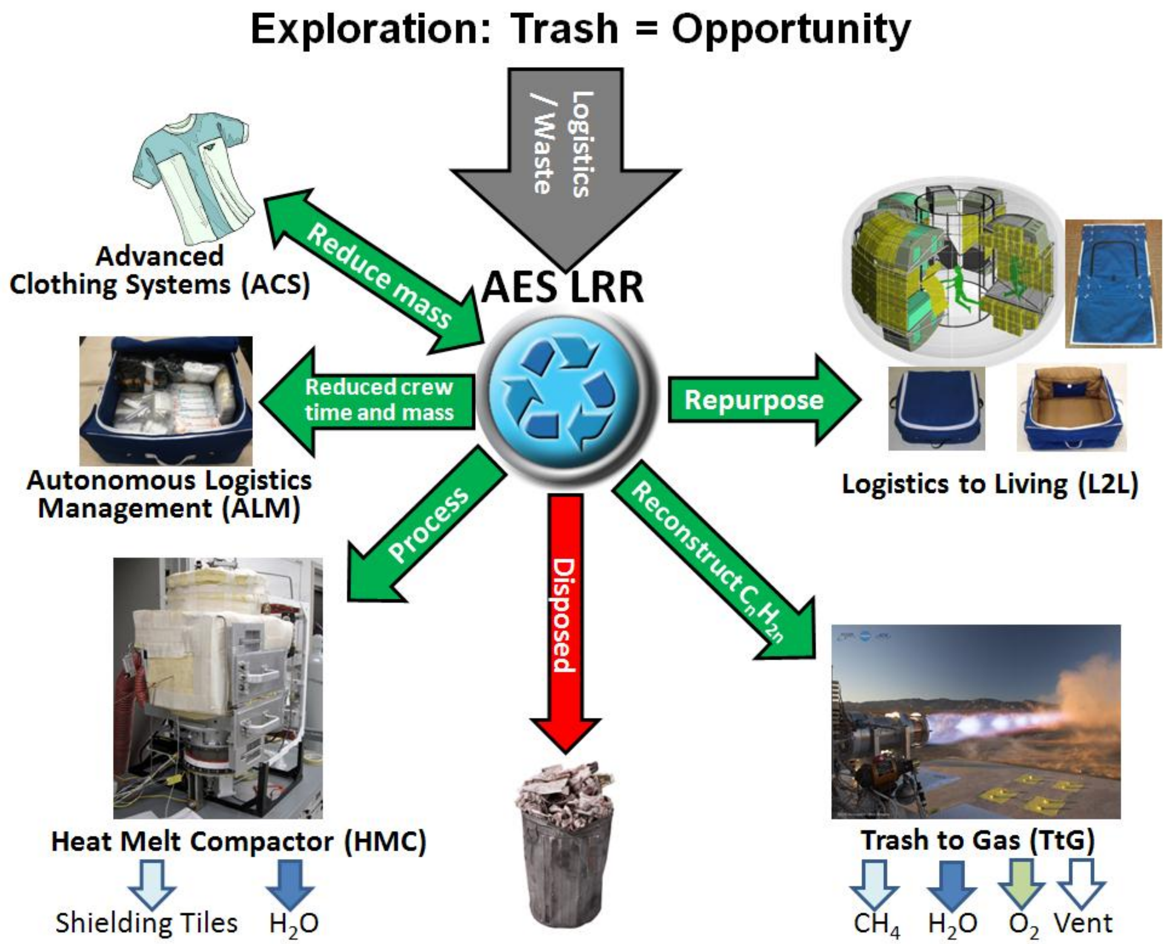

Figure 1. LRR technology overview.

II. LRR Technology Development and Status

During the 2-1/2 years of development, the LRR project has used a Systems Engineering and Integration (SE&I) team to guide technology development and evaluate different approaches.[2] A detailed exploration logistics and waste model was developed and was previously described. A summary of the results are listed here to characterize the mission challenges.[1] The model included crew consumables' mass and volume for a generic 1-year microgravity mission beyond low Earth orbit (LEO) for a crew of four. The total crew-related logistics add up to 5370 kg and 19.1 m^3. The total crew-related trash or waste add up to 2560 kg, which can be broken down into 1240 kg of trash, 660 kg of metabolic waste, and 660 kg of life support system consumables. This model continues to be refined and is being updated to include logistical consumption and waste generation rates throughout the mission. Additionally, the LRR SE&I function will use the LRR results to estimate the benefits of future technology development; e.g., laundry benefit for increasing mission durations.

A. Advanced Clothing Systems

Advanced lightweight and antimicrobial fabrics will increase the duration of clothing usability and reduce up-mass and disposal burdens. These benefits will help enable long-duration missions beyond LEO. Clothing accounts for a significant portion of the logistical mass launched on current space missions: 440 kg and 1.3 m^3 for an International Space Station (ISS) crew of six each year (not counting towels).[1] Since no space laundry is available, the clothing becomes trash when it is too dirty to wear. Advanced lightweight and antimicrobial fabrics that are currently used in some COTS garments have been evaluated for extended use during long-duration missions. Antimicrobial treatments and sanitation methods are also being tested to extend clothing's useful life and minimize consumables.

First, exercise clothing articles were selected and evaluated via flammability tests, functional tests, and during short-duration (1-2 week) ground tests with the AES Multi-Mission Space Exploration Vehicle (MMSEV) and the AES Deep Space Habitat (DSH).

Then, ACS developed the test protocols and human institutional review board approvals for a ground evaluation of multiple fabrics, with antimicrobial-treated and untreated garments. The test was completed in August 2013 with 76 participants. During the ground test, participants performed cardiovascular exercise for 1 hour a day for least 5 days a week in a controlled environement to simulate the exercise protocol used by crew members on ISS. The ground test investigated several variables with five types of garments. Garment fabrics (material and weave) that were tested included cotton, polyester, polyester/cocona blend, modacrylic, and wool. Cotton was used as the baseline because it is used in the majority of the ISS clothing inventory. These fabrics were either untreated or treated with a silane quaternary ammonium salt as an antimicrobial agent. The intent of the antimicrobial agent was to reduce microbial activity that can break down sweat compounds and create clothing odors. Excessive clothing odors are one of the parameters that can limit overall clothing usage life. The antimicrobial agent did not significantly improve performance of polyester, polyester/cocona, or wool, but did increase use time for cotton fabrics. However, untreated wool actually had longer use time than the antimicrobial treated cotton. Compared to the untreated cotton baseline, untreated wool could be worn about 80% longer in the ground study.

Figure 2. ACS clothing test at HI-SEAS.

ACS also provided exercise and sleep clothing to six test subjects for the 4-month 2013 Hawaii Space Exploration Analog and Simulation (HI-SEAS) analog test (Figure 2). The HI-SEAS data are currently being analyzed and compared to the NASA ground study.

The ACS team analyzed the time-of-use data and the test subject perception of clothing from the ground study to make the final selection of clothing for an ISS technology demonstration for Increments 39/40 (June-September 2014). The ACS team provided two types of exercise shirts, one type of exercise shorts, and two types of routine-wear shirts. The selection provided a range of fabric types (e.g., wool, polyester, and modacrylic) and weaves based on the ground study test results, and 180 clothing articles were processed for a flight launch on ATV5 in June 2014 (Figure 3). Prelaunch crew evaluations are being performed for each of the US and Russian crew members to establish a terrestrial baseline. Training/familiarization videos are being developed for on-orbit use prior to initiating the ISS experiment. The crew will complete periodic evaluations and record data for analysis. Crew debriefs will be conducted in 2015 after the crew returns from orbit. The results of the ground and on-orbit tests will be published in the summer of 2015.

Figure 3. Portion of ACS clothing delivery for ISS Technology Demonstration.

B. Logistics-to-Living

L2L is defined as repurposing or converting logistical items (containers, foam, components, etc.) into useful crew items or life support augmentation on-orbit after the items have provided their primary logistics function. The intent is that by repurposing items, dedicated crew items do not have to be launched, thus the overall launch mass is decreased. For non-LEO missions, the vehicle interior volume will be relatively fixed. L2L will enable this volume to be used more effectively through repurposing and conversion of logistical components.

Several of the L2L concepts are based on CTBs, which are currently used like suitcases to transfer logistics cargo to the ISS. A high percentage of logistics supplies is packaging mass; for a 12-month mission, a crew of four will need over 170 CTBs if similar to ISS. CTBs are used for on-orbit transfer and storage but eventually become waste. The LRR CTB reuse investigation considers innovative interior habitat outfitting as a way to repurpose CTBs. This outfitting would provide multiple functions: launch packaging, stowage, radiation reduction water wall, as well as structure. Reuse of these CTBs would reduce the amount of waste generated and also significantly reduce future up-mass requirements for exploration missions. A future goal in coordination with the AES Water project is integrating water processing features into the CTBs for contingency operations.

Early in the project, the L2L team focused on creating a multi-purpose CTB (MCTB) and demonstrating its usage as partitions in the DSH.[3] MCTBs can be unfolded from a suitcase shaped volume to a flat panel on-oribit so that the MCTB can be used for outfitting functions. Next, the L2L task refined the basic MCTB snap and zipper construction based on the results of structural launch load tests of corner and handle coupons. Five specific applications of MCTBs were investigated: a MCTB for deploying HMC tiles as part of a radiation storm shelter, an acoustic blanket MCTB for reducing ISS treadmill noise, an ALM dense reader MCTB outfitted for RFID tagged logistics, an L2L-derivied crew quarters (CQ), and a forward osmosis MCTB for waste water processing.

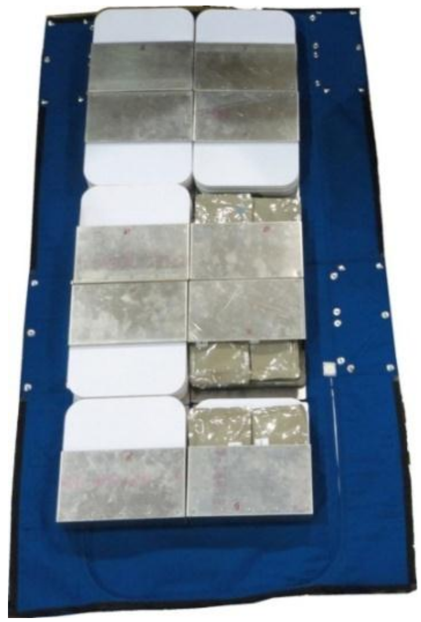

Figure 4. Radiation storm shelter wall component concept constructed from unfolded MCTB (blue fabric) with pockets for HMC tiles (white foam squares) and food packages (grey-brown packages).

This year, L2L is prototyping MCTB applications. In addition, the L2L team worked closely with the HMC and AES Radiation Protection project teams to determine how MCTB could help provide additional radiation protection. The MCTBs would have pockets or straps to initially hold thermostabilized food packages (which have high water content). As the food is used from the pockets or strap, HMC tiles would replace them to maintain the radiation shielding (Figure 4).

The acoustic MCTB prototype developed in 2013 has completed acoustic transmission coupon tests. The acoustic MCTB has been modeled while deployed against the ISS waste and hygiene compartment wall and adjacent walls by the NASA Johnson Space Center Acoustics Office (Figure 5). Preliminary results indicate a 3-decibel reduction is possible, which represents a 50% reduction in sound power level. Additional testing and feasibility assessments are under way to investigate the feasibility of deploying the acoustic MCTB on the ISS as a technology demonstration in 2015. The technology demonstration would evaluate crew acceptance during deployment, evaluate acoustic noise reduction, and validate logistics stowage volume saving estimates.

The L2L project also developed several prototype RFID-shielded MCTB for the LRR ALM task. The second-generation RFID MCTBs incorporated improved shielding of zippers and antenna feed options. The L2L project goal is to have a flight-like design (acoustic- or RFID-based) complete by the end of 2014 that could be built and flown in 2015. The RFID-MCTB is described in greater detail under the ALM technology description.

The L2L-derived CQ work is on hold until mid-year to allow the AES Exploration Augmentation Module (EAM) project to first determine whether a CQ function is required. The L2L project also investigated insertion of bladders into the MCTB for water processing, and several protypes were fabricated. Waste water could be pumped on to one side of a forward osmosis membrane, while an osmotic agent on the other side draws clean water across the membrane. Details of this technolgogy have been previously described.[4]

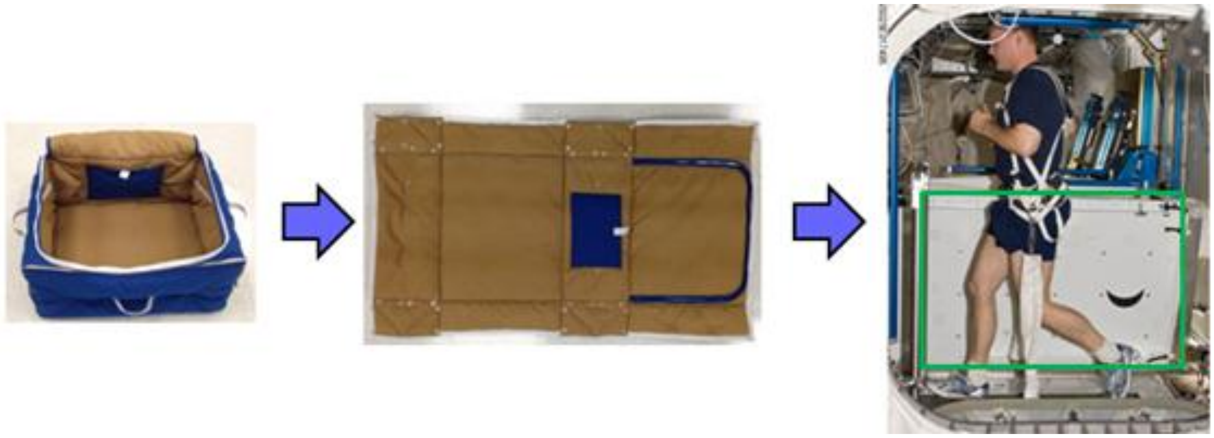

Figure 5. Repurposing of L2L MCTB for mounting on ISS Waste and Hygiene Compartment wall to mitigate treadmill acoustic noise.

Additionally, alternatives to packaging foam were investigated with a NASA@work InnoCentive® challenge. The investigation revealed that approximately 50% of the foam usage is driven by the need to pack in a way that minimizes crew time needed on-orbit to locate items, leading to an opportunity to reduce foam when ALM technologies are implemented. Foam was tested in the HMC to determine compaction and off-gassing properties. L2L also used student participants for developing random access frame concepts at the NASA Jet Propulsion Laboratory (JPL) and as part of the AES DSH eXploration Habitat (X-Hab) Academic Innovation Challenge with the University of Alabama Huntsville. In addition to the stowage frame by the University of Alabama, the NASA JPL worked with students to develop a random access frame that was completed late 2013 and delivered to the University of Maryland for use as a test article in their neutral buoyancy facility. The University of Maryland activity was funded by an AES DSH X-Hab project.

C. Autonomous Logistics Management

The LRR ALM activity was initiated midway through 2013. ALM is tied to the L2L task for soft goods and potential MCTB applications but is a distinct technology area. ALM is a broad area and was identified by the National Research Council review of the Office of Chief Technologist TA07 roadmap as a high priority area. The LRR ALM activity will focus on a subset of ALM functions: automated RFID-tagged logistics reading and 3D localization of RFID-tagged items. These two functions have the potential to dramatically reduce on-orbit crew time required to perform general inventory management and searching for lost items. As indicated under the L2L section, minimizing crew time on logistics would allow items to be packaged for volume efficiency rather than crew-time efficiency. This improved efficiency could greatly reduce the amount of foam that is launched. ALM should allow rapid location of items in densely packed CTBs, hence minimizing the need for up to 50% of the foam, which should allow for denser packing of the same items and, in turn, fewer CTBs, resulting in decreased mass and volume for a given mission.

Mid-2013, a RFID MCTB was built with a conductive fabric layer sewn into the MCTB walls to contain the electromagnetic fields used to read the RFID-tagged contents inside the bag. The conductive wall prevents reading tags external to the MCTB to ensure only items inside the MCTB are identified. The RFID reader is based on the reader previously built for use on the ISS Medical Project 2-drawer pantry that arrived on the ISS in August 2013. The RFID reader reports the contents of the bag to a database via a WiFi connection. E-textile antennas were fabricated to minimize weight and provide desired physical flexibility. The placement of the RFID antenna feeds was optimized to maximize reading performance. Testing indicated some radio frequency (RF) energy is leaking from the zippers and folded corners of the RFID MCTB and can result in the reader reporting tagged items located outside the bag. External reads are not desirable because they would be reported as within the MCTB when they physically are not. This could result in lost crew time from mistakenly looking inside a bag. Thus, further work is needed in this area.

Currently, LRR ALM is focusing on three technology areas: sparse-area RFID readers, dense-area RFID readers, and radio frequency identification enabled autonomous logistics management (REALM) application development. Analysis and testing of sparse-area readers will be performed to enable a 3D localization architecture recommendation for node-like and module-like vehicles. These recommendations will include details about reader number and layout verses 3D localization resolution. Figure 6 shows a test setup to examine the use of sparse zone RFID readers in an ISS element analog. Studies include the use of fixed readers to track tagged items in transit, during usage, and while stowed. For dense-area readers, a second generation MCTB, redesigned to minimize RF leakage, will be outfitted as a dense reader to determine the RFID shielding effectiveness and read accuracy. Since neither sparse nor dense readers can be 100% accurate due to reflections, obscured signal path, and vehicle layout, REALM provides the operational intelligence to fill in the localization gaps. An initial REALM software application using complex event processing will be developed to provide intelligent estimation of item location based on previous location and community relationships from dense and sparse reader data. Initial implementation to gain confidence in the system might compare the latest results of dense enclosure stowage bag query to current methods of inventory tracking. Once the system is proven, the software could update inventory changes automatically. Details of operational procedures could later be defined by operations personnel and incorporated into the software so that location of items needed for a task becomes automatic.

The ALM technologies will be demonstrated in 2014 to representatives of the ISS Program, Crew Office, Mission Operations, and Human Health and Performance organizations. The goal is to demonstrate basic ALM functionality and develop future collaboration for a potential ISS technology demonstration in 2015. AES LRR is investigating collaborating with academia and the small business innovative research program in 2015 to leverage additional expertise.

Figure 6. Red circles mark antennas for the sparse area reader.

D. Heat Melt Compactor

The HMC task is developing a high reliability technology for recovering water from waste materials and producing dry, sterilized, plastic encapsulated, low-volume tiles for radiation protection, storage, or disposal. A full-scale second generation (Gen2) HMC has been developed with the goal of advancing the technology to Technology Readiness Level 6. Multiple NASA centers have participated to address the following development activities: mission benifits analysis; thermal system analysis; structural analysis; microgravity component evaluation and testing; gaseous trace contaminant control; system operational control; power supply control; chemical and biological characterization of tiles; and characterization of output water quality to allow assessments for future water recovery processes. Figure 7 shows the Gen1 HMC currently being tested and Figure 8 shows the design of the Gen2 HMC.

The Gen2 HMC will be able to process about 1 kg of typical trash and recover about 200 ml of water from each batch run. The full process, including warm up, processing and cool down will take hours. During ground testing with Gen2, many operational parameters such as heater power and cycle times will be studied and optimized.

Figure 7. First generation HMC used for process development testing.

Initially the HMC project focused on testing the existing Gen1 HMC unit to obtain detailed chemical off-gassing and water condensate constituents.[5] These data supported development of a source contaminant control system for Gen2. Additionally in the first year of the project, the Gen2 requirements and preliminary design were completed. The Gen2 HMC design is targeting an EXpedite the Processing of Experiments to Space Station (EXPRESS) Rack interface to enable design transition to an eventual ISS technology demonstration. During the Critical Design Review, an option of operating the unit at near-atmospheric pressure rather than reduced pressure was identified, and a trade study indicated it could be beneficial for significantly simplifying the system. Gen1 HMC is being used to develop test data to determine whether atmospheric pressure processing is possible. Gen1 HMC is also being used to conduct a limited number of foam compaction tests to determine the best operating conditions to obtain efficient compaction and identify gas effluent constituents.[6,7]

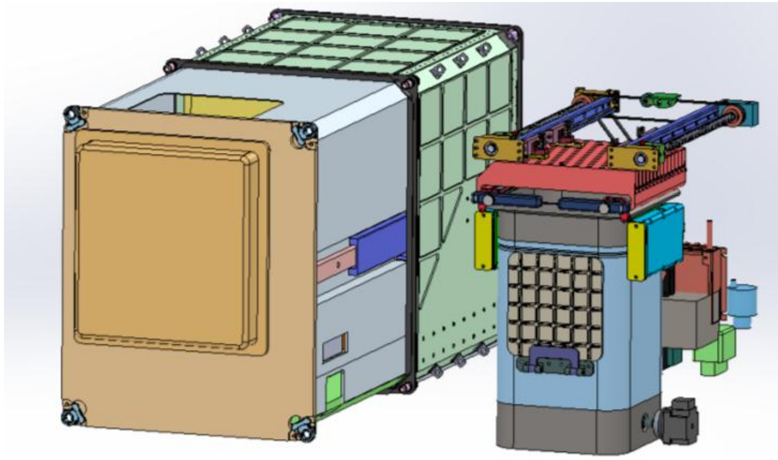

Figure 8. Second generation HMC design.

The current year's requirement is to fabricate and assemble the core compaction chamber assembly by September 2014.[8] The major chamber parts have been machined and surface treated (Figure 9). The remaining chamber parts, control instrumentation, and electrical control system parts are in work. The HMC source contaminant control system is being provided by the AES Atmosphere Resource Recovery and Environmental Monitoring Project. It consists of a carbon adsorption bed that protects a novel thermo catalytic reactor from a phase III small business innovative research contract.

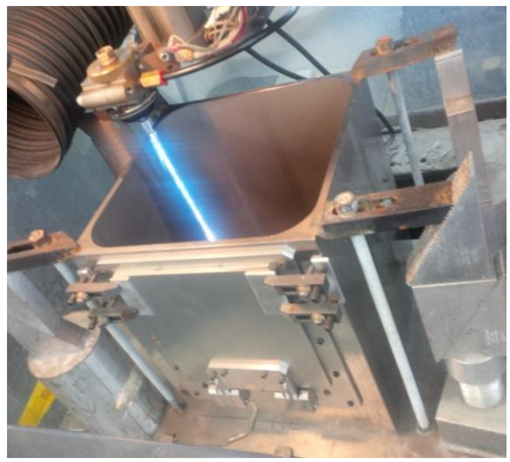

Figure 9. HMC middle compaction chamber during machining.

The HMC team plans to assemble the supporting ground equipment this year and conduct a limited number of mixed trash runs on Gen2 HMC to check out the system and gather data to compare to design predictions. Then, additional runs on the Gen2 unit will be conducted to determine the robustness of the system. When all the Gen2 HMC required tests are completed at Ames Research Center, the unit will be delivered to Johnson Space Center for future integration tests with other life support systems.

E. Trash-to-Gas

The overall goal of the TtG task is to develop space technology alternatives for converting trash and other waste materials into gases that can be easily vented as a 'jettison function' or converted into high-value products. The products being evaluated include propellants, and life support oxygen and water. This reuse of discarded materials is an effective method for reducing overall mission mass. The TtG team, along with LRR SE&I analysis, is determining the feasibility and benefits of this approach. The overall technical approach for TtG has been to adapt technology already developed by industry for terrestrial applications for use in space and ensure that the results of this work are available for spin-off applications back on Earth. Along those lines, candidate technologies have been tested with identical prototypic waste inputs to determine process efficiencies. The test results were then combined and compared analytically to calculate the overall production rates and equivalent system masses (ESMs) of the various competing systems. ESM is a technique for normalizing mass, power, and volume to a single 'equivalent' launch mass number.[9]

In the first year, TtG successfully demonstrated six thermo-chemical technologies for processing of simple wastes.[10,11] Data from each technology were presented at a technical interchange meeting in 2012. Wastes used in the tests were identified from a model of waste generated during long-duration space flight and included a food packaging simulant, cotton washcloths, Maximum Absorbent Garments, food, and human waste simulants. *Pyrolysis* produced a mixed gas of hydrocarbons, carbon monoxide, carbon dioxide, and a small amount of methane. *Gasification* and *incineration* produced mostly carbon dioxide, with smaller amounts of carbon monoxide, unreacted hydrocarbons, and trace amounts of methane. The *catalytic reduction* process directly produced about a 25% yield of methane from polyethylene. The remaining gases included carbon dioxide and carbon monoxide. The *steam reformer* was shown to convert the waste into a gas mixture predominantly composed of carbon dioxide, carbon monoxide, and hydrogen. *Ozone oxidation* tests were performed with the prototypic waste and fecal simulants, and were shown to oxidize the waste to carbon dioxide. Data from the experiments were used to update models used for efficiency analysis.

During the second year, further tests of the six technologies were conducted using higher-fidelity waste streams. The TtG team developed key performance parameters for down-selection and defined process constraints (i.e., hydrogen limited or carbon limited). Performance parameters were based on multiple mission scenarios including methane production, venting of gases, and production of gases for resistojet propulsion or life support. An August 2013 technology down-select technical interchange meeting successfully compared technologies and concluded that, based on hardware currently available to NASA, one technology outperformed the other five for both resitojet mixed gas and methane gas propulsion scenarios. Steam reforming technology was selected for continued technology development based on testing data provided by Pioneer, Inc. on a phase II small business innovative research (SBIR) contract. The SBIR system was delivered to NASA Glenn Research Center in 2013 (Figure 10).

Figure 10. SBIR Phase II Steam Reformer.

Calculations have shown that much more mass of propellant can be produced from the waste stream than will be required to launch the waste processing reactor.[12,13] This reactor would likely be located outside of the crew volume for safety reasons, so details must still be worked out. In addition to the down-select analysis and technical interchange meeting, the TtG and SE&I teams performed a trade study of trash jettison vs. trash processing to quantify the mission benefits of both methods.[14]

Funding in the current year has been very limited for the TtG activity but some progress is still being made. The major goal of the TtG team is to setup and test the Pioneer SBIR steam reformer at NASA Glenn Resarch Center to independently verify the production rates and gas purity. The TtG team is also utilizing the NASA Kennedy Space Center's TtG incinerator with a commercial steam generator to simulate the Pioneer reactor for certain experiments. Additionally, the TtG team is analyzing and preparing designs for hardware that will introduce waste into the reactor in a microgravity environment.

III. Conclusions

The AES LRR project has demonstrated through technology development testing and systems analysis that it is feasible and benifical to reduce spacecraft logistical burden by repurposing logistics for secondary use and processing waste to increase habitatable volume, provide microbial stabilization, and decrease up-mass. The five current LRR technologies represent a broad range of reduce, reuse, recycle, repurpose, and reformulation approaches. Progress on each of these initiatives has been reported here. Previous and future papers will provide more details on the benefits of these technologies[1]. By the end of the third year of the LRR project, recommendations will be provided for future mission logistics, habitation outfitting, and waste processing. Additional development is required to bring these technologies to flight readiness for exploration missions; however, good progress has been achieved by the AES LRR project.

Acknowledgments

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